The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures

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LONG-TERM GOALS

The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering and transmission in bubbly mixtures pertinent to the shallow-water ocean-acoustics scenario. This includes a conceptual understanding of the role played by stabilization mechanisms in bubble dynamics and longevity. Of particular interest is the phenomenological delineation of different regimes of behavior.

OBJECTIVES

An objective specific to this project is the extension of the theory of sound transmission in bubbly liquids to derive attenuation characteristics for both small amplitude (linear response) and large amplitude (nonlinear response) forcing, ultimately incorporating the effects of contaminating surface-active solutes. A second objective is the development of a unique laboratory capability for the precise and accurate measurement of the frequency-dependent complex acoustic impedance of, scattering from, and propagation through well-characterized bubble clouds *for frequencies spanning the individual bubble resonance frequencies*. Cloud characterization implies the precise knowledge of all bubble population statistics, both spatially and size-wise.

APPROACH

All aspects of the work proceed in collaboration with William Carey of NUWC. Also involved is BU Prof. Greg McDaniel (data analysis and modeling) as well as two BU graduate students (one supported

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by a BU Fellowship. Dr. Carey has recently taken a faculty position with Boston University, where he will continue to serve as co-investigator for the ongoing research effort.

The approach involves a balance between modeling and experiments to predict and measure propagation and scattering characteristics. A core issue is the dynamics of a single bubble for both small and large amplitude forcing. This is handled numerically using the Keller formulation for bubble dynamics. The attributes of bubble behavior (mainly damping and resonance response) can be quantified and incorporated into a comprehensive description of sound propagation and scattering by extending the Wood-Foldy-Morse theories. The final step is to incorporate the effect of surface active materials by adapting numerical models developed by Church [1995] and Allen [1997], among others.

Laboratory experiments cover two fronts of activity. FY99 efforts focused on the measurement of the complex impedance of bubble distributions terminating a sound-hard impedance tube over frequencies ranging from well below to well above bubble resonance. The bubbly medium can be characterized optically using a stereo microscope and electrically by way of conductivity measurements to determine void fraction. A variant of the dual-sensor impedance tube technique is employed. From this, the frequency-dependent phase velocity and attenuation of the bubbly medium is obtained.

The second experimental thrust, planned for FY00, is the development of a thin-walled pulse tube for measuring the backscatter from, and transmission through, bubble filled test sections. The tube will operate between 15 and 30 kHz and is long enough (order 15 meters) to accommodate narrow-band gated-cw pulses. With this geometry, 1-D (plane wave) scattering experiments can be carried out in a wave-guide for which the characteristics of the scattering media is well know and boundary interactions are rigorously accounted for. The pulse tube and cw experiments will proceed in close coordination.

WORK COMPLETED

The FY 99 research effort focused on the experimental plan. The impedance tube apparatus was developed (see Fig. 1) and initial measurements performed. A special transducer design was developed to allow sound generation at the entrance of the test apparatus while at the same time mechanically isolating the transducer from the wall of the test tube. A significant amount of time and effort was devoted to a careful quantitative characterization of the tube and to the development of high-impedance wall mounted receivers for sensing the field without affecting propagation. Preliminary results agree with our own model calculations as well as those of Lafleur & Shields [1995] in all respects except for frequency-dependent damping. We are presently developing a damping model with accurately accounts for radiation damping and will be incorporated into the propagation models for both the thick-walled impedance tube and the thin-walled pulse tube.

Bubble-filled test fluids were developed using two novel techniques. Freely rising micro-bubbles were generated using a rotating porous cylinder though which air is forced [Chiba & Takahashi, 1998]. Bubbly distributions were also created by suspending micro-bubbles in a 1% solution of Xanthan gum. The advantage of the latter technique is the bubble distributions in both size and space are stationary in time and easy to characterize. The disadvantage is that the impact of the viscoelastic suspending gel is not known. To address this latter point, we are assembling an experimental apparatus in which the dynamic response of a single bubble suspended in the polymer gel and driven acoustically. The frequency-dependent response of the bubble is going to be measured using laser Mie scattering and compared with model predictions of bubble dynamics in Newtonian and viscoelastic media.

RESULTS

A typical result obtained with the impedance tube apparatus is shown in Fig. 2, which displays the frequency-dependent magnitude and phase of the reflection coefficient for two bubble distributions with differing void fractions. The peak in the bubble distribution corresponded to a resonance frequency that is larger than the upper frequency limit for the measurement, thus is it expected that the reflection coefficient in both cases should be real and approximately equal to -1, with the larger void fraction measurement yielding a larger (more negative) reflection coefficient. Those trends are clearly indicated in the data, which was obtained using a gel based bubble distribution.
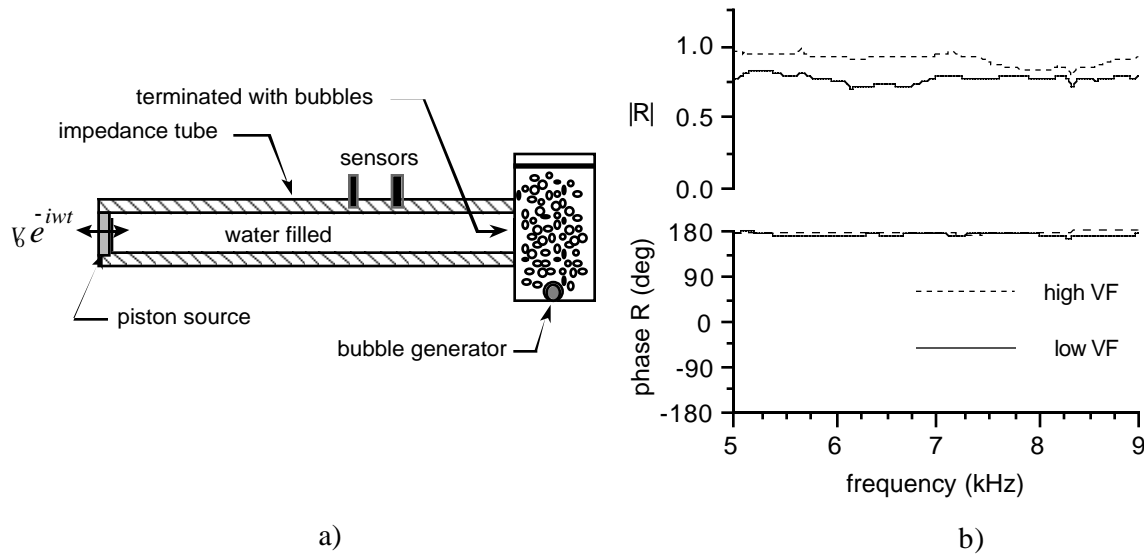
1. (a) Impedance tube apparatus. (b) Measured complex reflection coefficient of two polymer-stabilized bubbly suspensions.

Results were also obtained using a bubble-free polymer termination and a water termination (i.e. an open ended tube). In both cases, results agreed with theoretical predictions, however some artifacts were observed in the data that suggest that a more accurate sensor phase calibration is required with probing samples with low intrinsic attenuation. The technique for processing the impedance tube measurements to obtain the termination impedance is described in [ASTM, 1990], where a swept sine excitation was employed. The technique is both precise and fast, the latter of which is important if one want to modify the apparatus for at-sea measurements bubbly distributions that are non-stationary in time.

IMPACT/APPLICATIONS

The notion that bubbles can be driven to pulsate collective is important to any assessment of scattering and attenuation from oceanic bubble clouds and layers. The area of research is important to HF/SW noise and propagation, SW mine hunting sonars, high power acoustic arrays for MCM, and wake homing torpedoes. Furthermore, the acoustical measurement of bubble populations and circulation patterns may depend on the physics of multiple scattering and absorption in bubbly mixtures

RELATED PROJECTS

1 - A collaboration with NUWC/Newport (R. Costa) and CSS/Panama City (K. Commander) on an instrument designed for *in situ* measurement of oceanic bubble dissolution rates. The instrument was successfully deployed as part of a wake physics sea test at Nanoose in September, 1998 and the results were published in the Proceedings of Oceans '99 [Costa et al., 1999].

2 - A collaboration with APL/UW (S. Kargl) on the physics of nonlinear beam forming. The issues of bubble-mediated enhanced nonlinearity and dissipation in bubbly water are key to both projects. The goal of the beam forming project is to assess the viability of high-intensity sound beams for MCM.

3 - A collaboration with Univ. Virginia (J. Allen) on developing new theories that describe the dynamics of bubbles in viscoelastic media. The PI was the research advisor for J. Allen, a UW Ph.D. student in Mechanical Engineering who completed his dissertation September '97.

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